STUDIES ON SUBMARINE CONTROL FOR PERISCOPE DEPTH OPERATIONS

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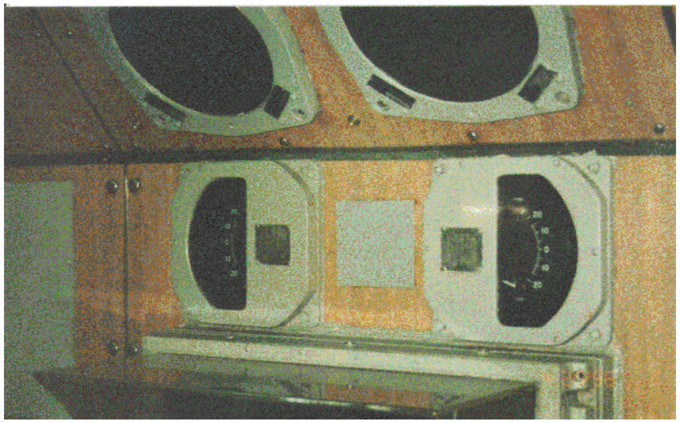
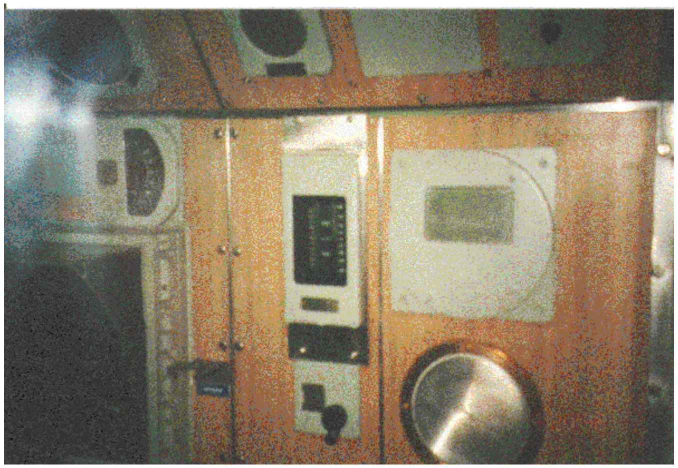
Overview

- INTRODUCTION
- SUBMARINE DYNAMICS MODEL
- WAVE FORCE MODELING
- STATE FEEDBACK CONTROL AT PERISCOPE DEPTH
- SLIDING MODE CONTROL
- GRAPHICAL DISPLAY
- CONCLUSIONS AND RECOMMENDATIONS

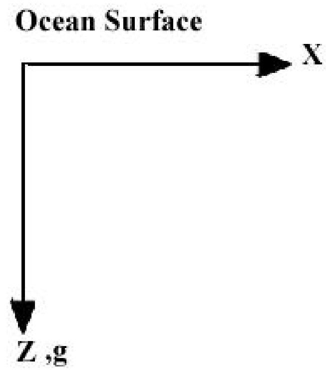
Introduction

- Changing missions add to SSN Periscope Depth (PD) time
- Display system not optimized for PD
- Evaluate control schemes for PD effectiveness and extrapolate display needs

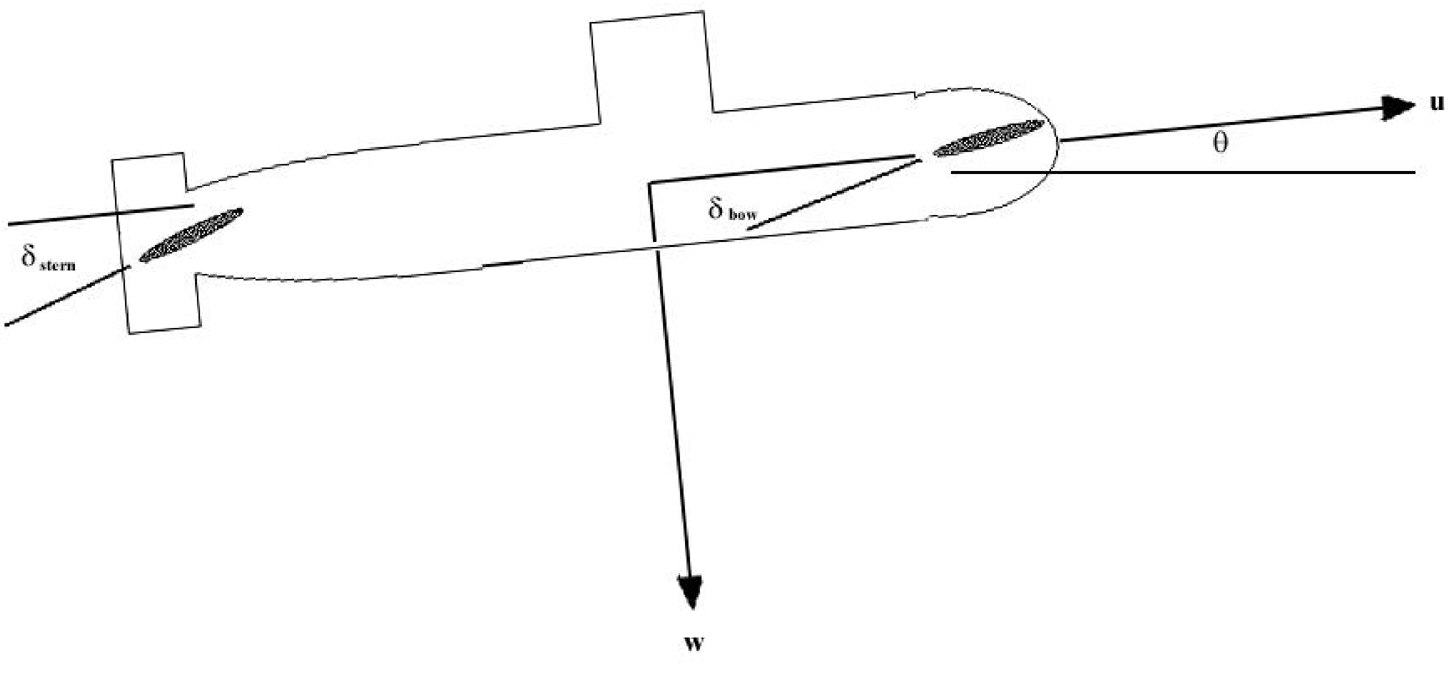




Submarine Dynamics Model



$$
\begin{bmatrix} \dot{w} \\ \dot{q} \\ \dot{\theta} \\ \dot{z} \end{bmatrix} =
\begin{bmatrix} a_{11}u & a_{12}u & a_{13} & 0 \\ a_{21}u & a_{22}u & a_{23} & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & u & 0 \end{bmatrix}
\begin{bmatrix} w \\ q \\ \theta \\ z \end{bmatrix} +
\begin{bmatrix} b_{11}u^2 & b_{12}u^2 \\ b_{21}u^2 & b_{22}u^2 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}
\begin{bmatrix} \delta_b \\ \delta_s \end{bmatrix} +
\begin{bmatrix} F_d \\ M_d \\ 0 \\ 0 \end{bmatrix}
$$



Submarine Dynamics Model

- DARPA SUBOFF coefficients
  - bow planes and metacentric height assumed
- Simplifying assumptions
  - Constant forward speed, u
  - Center of Buoyancy (CB) and Local Coordinate Origin collocated
  - Center of gravity directly below CB

Wave Forces

- JHUAPL provided data for sea states three and four, beam and head seas
- Spectra divided into *n* segments
- First order motions and second order forces determined based on *n* linear waves for SUBOFF using slender body theory
- Scaled for depth
- Added to equations of motion

Optimization Scheme

- Matlab CONSTR function (BFGS)
- Minimize RMS Depth error
  - 3 Levels of state feedback and sliding mode
    - Basic
    - Disturbance Feedforward
    - Integral Control

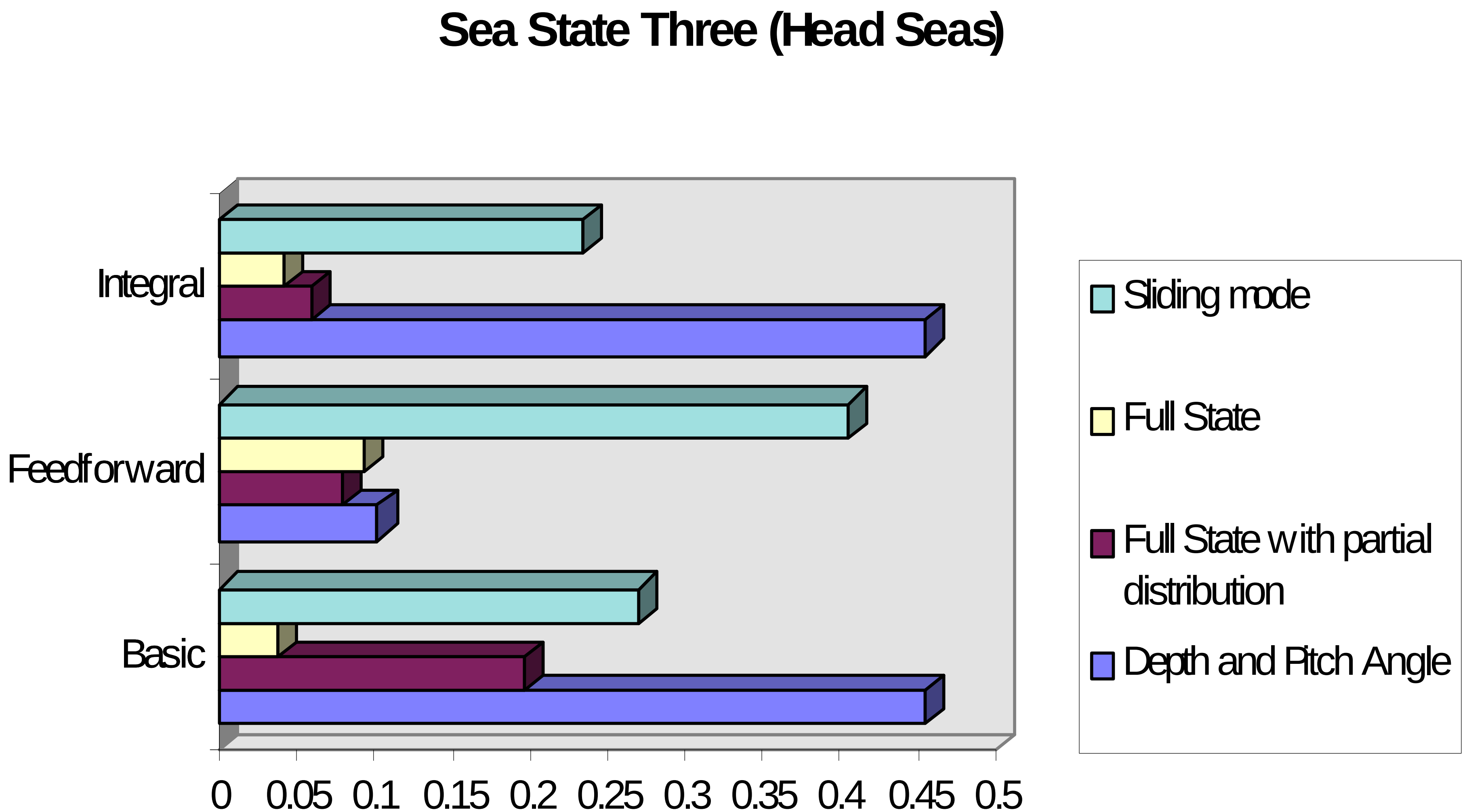
State Feedback Control

- Depth to bow, pitch angle to stern
- Depth and heave to bow, pitch angle and rate to stern (Full state partial distribution)
- Full state
- Each repeated with
  - disturbance feedforward
  - integral depth control

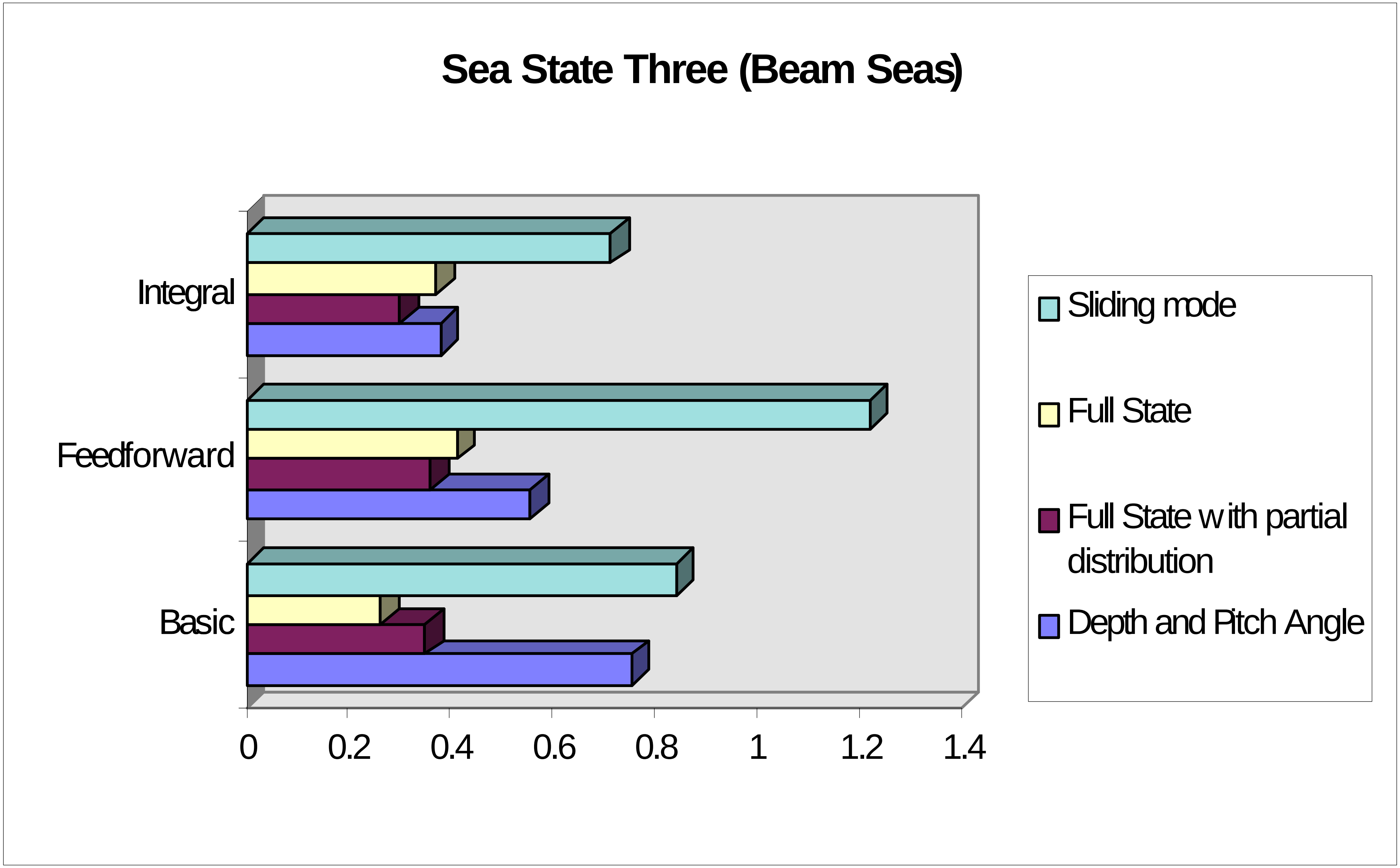
Sliding Mode Control

- Disturbance response studies
- Basic
- Disturbance feedforward
- Integral control on depth

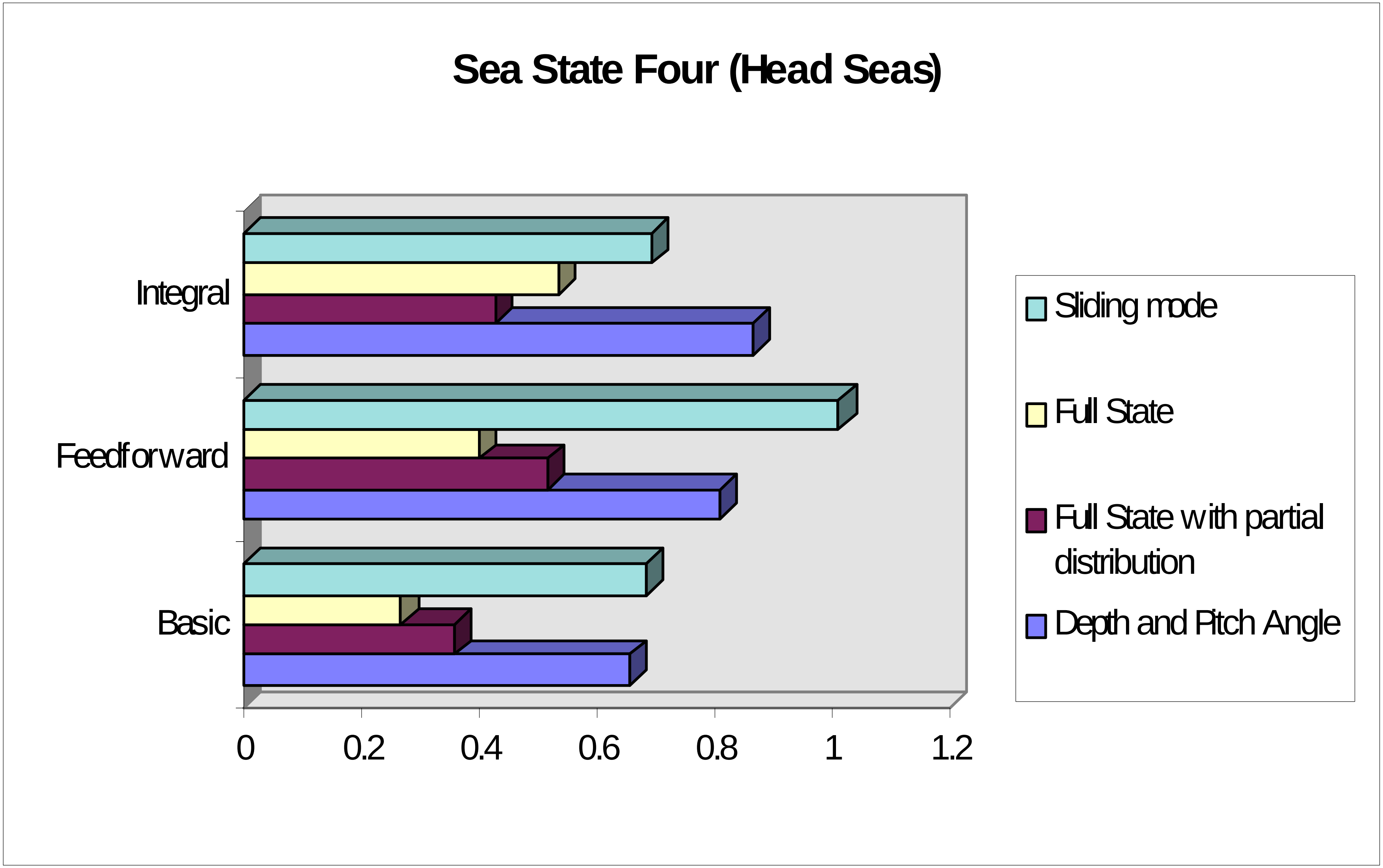
Control Law Optimization Results



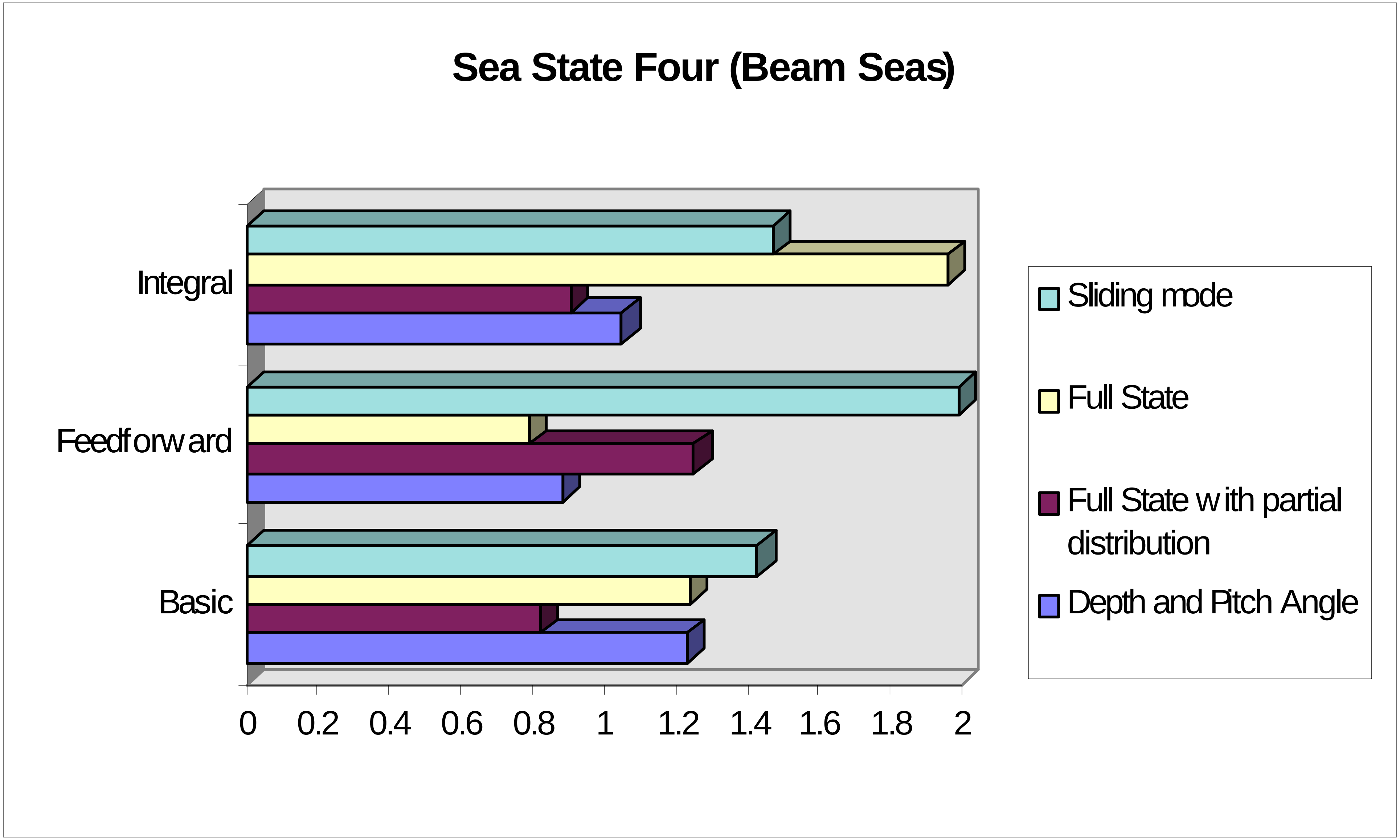
Control Law Optimization Results



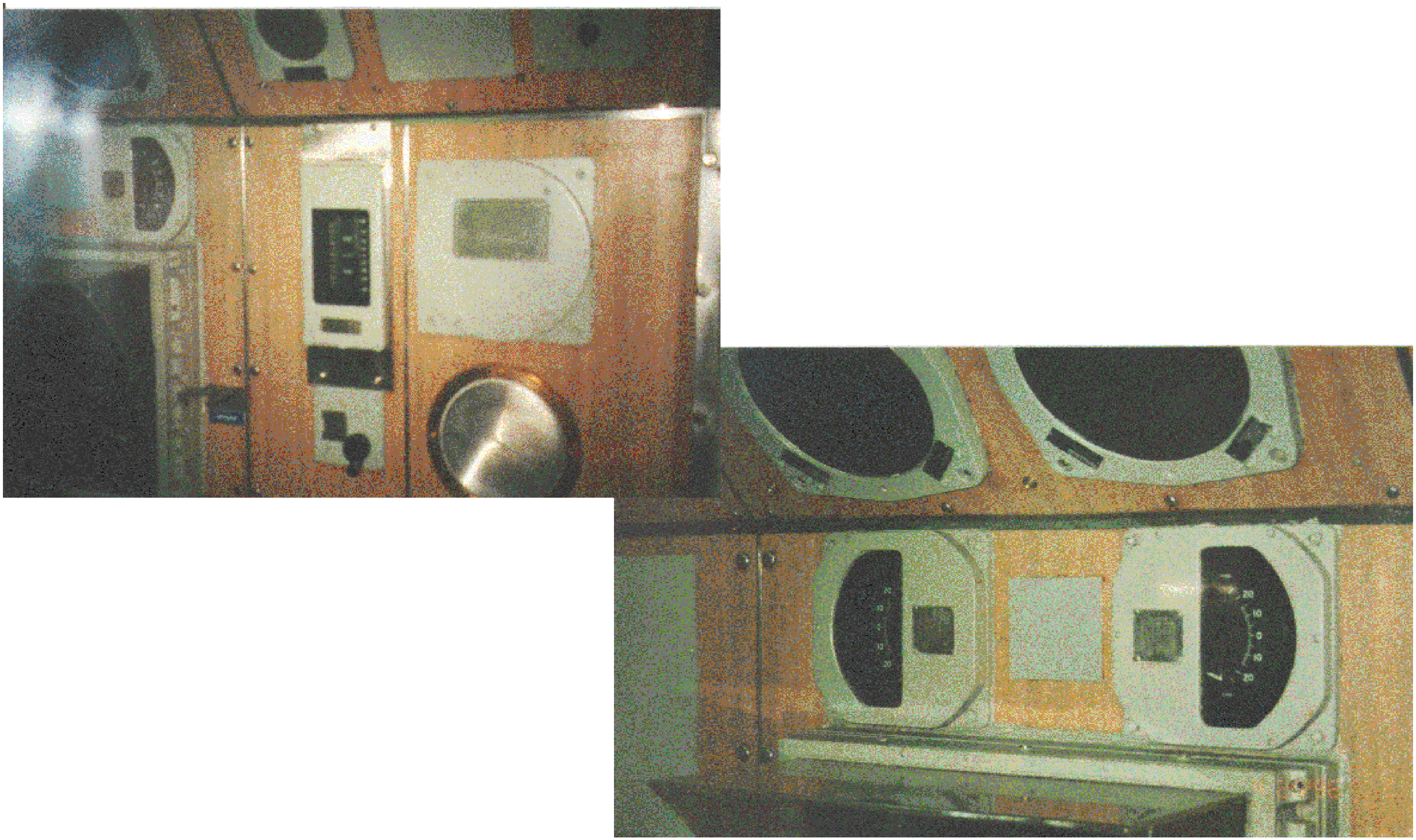
Control Law Optimization Results

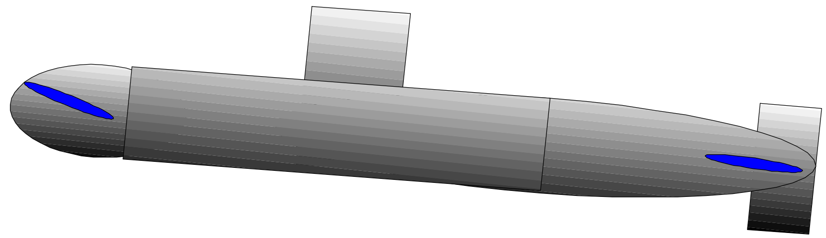


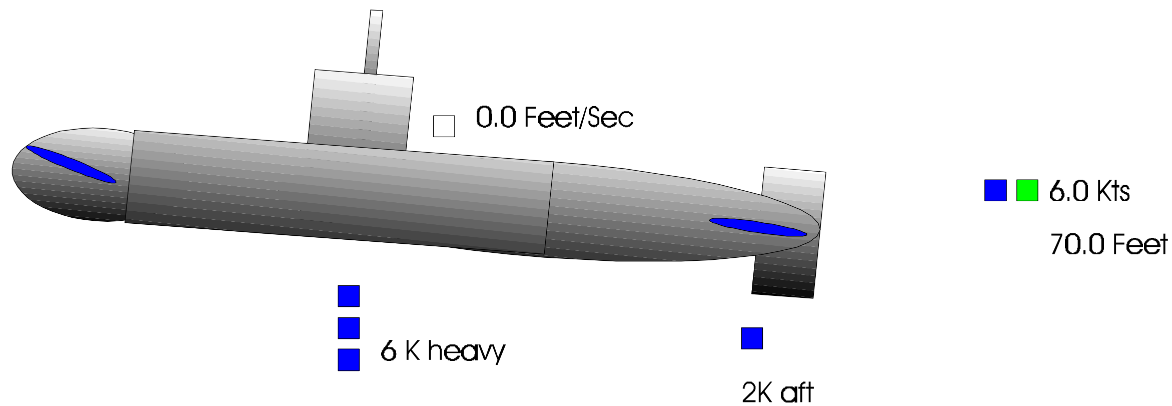
Control Law Optimization Results



Graphical Display



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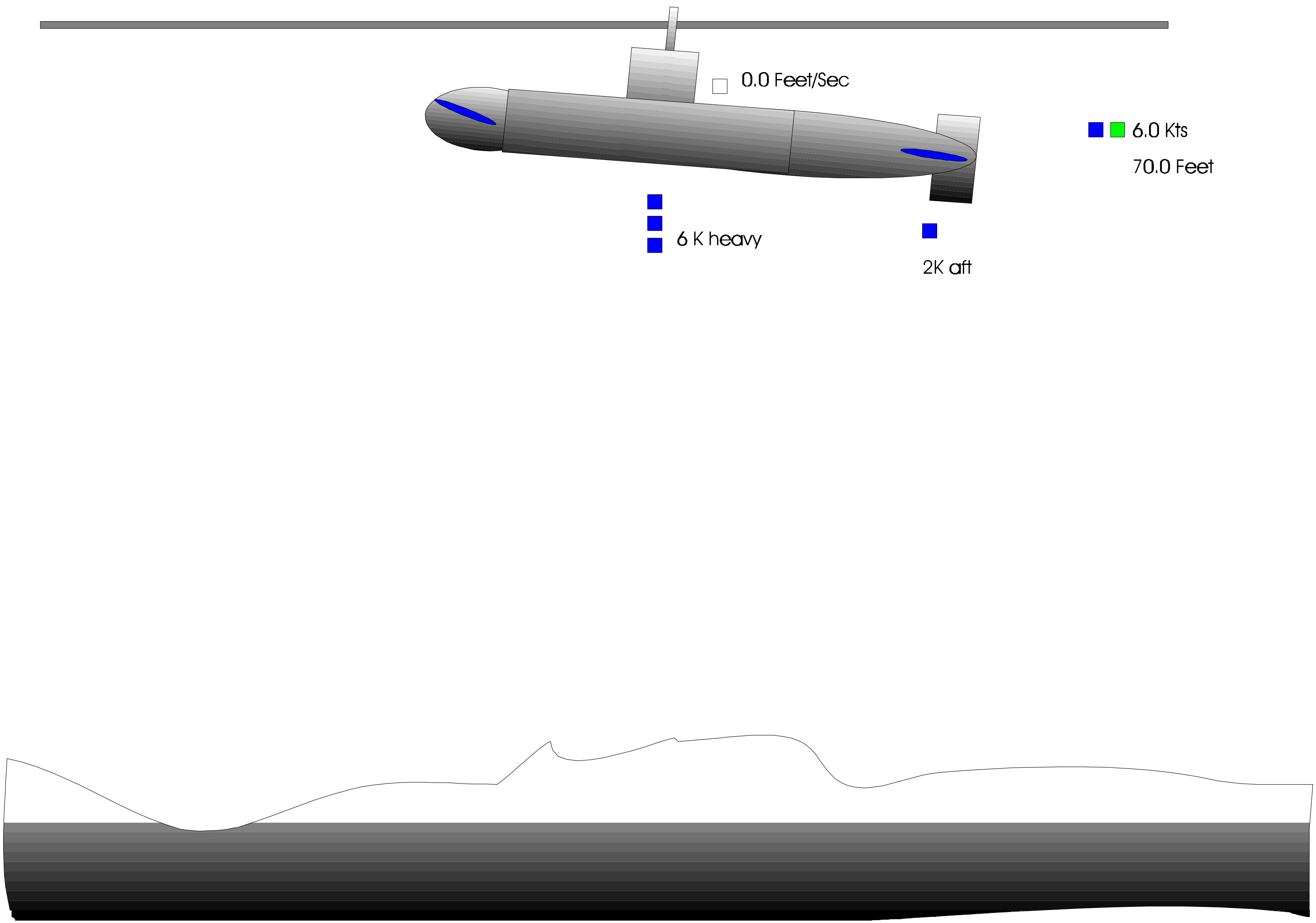
6.0 Kts
70.0 Feet
6 K heavy
2K aft


0.0 Feet/Sec
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6 K heavy
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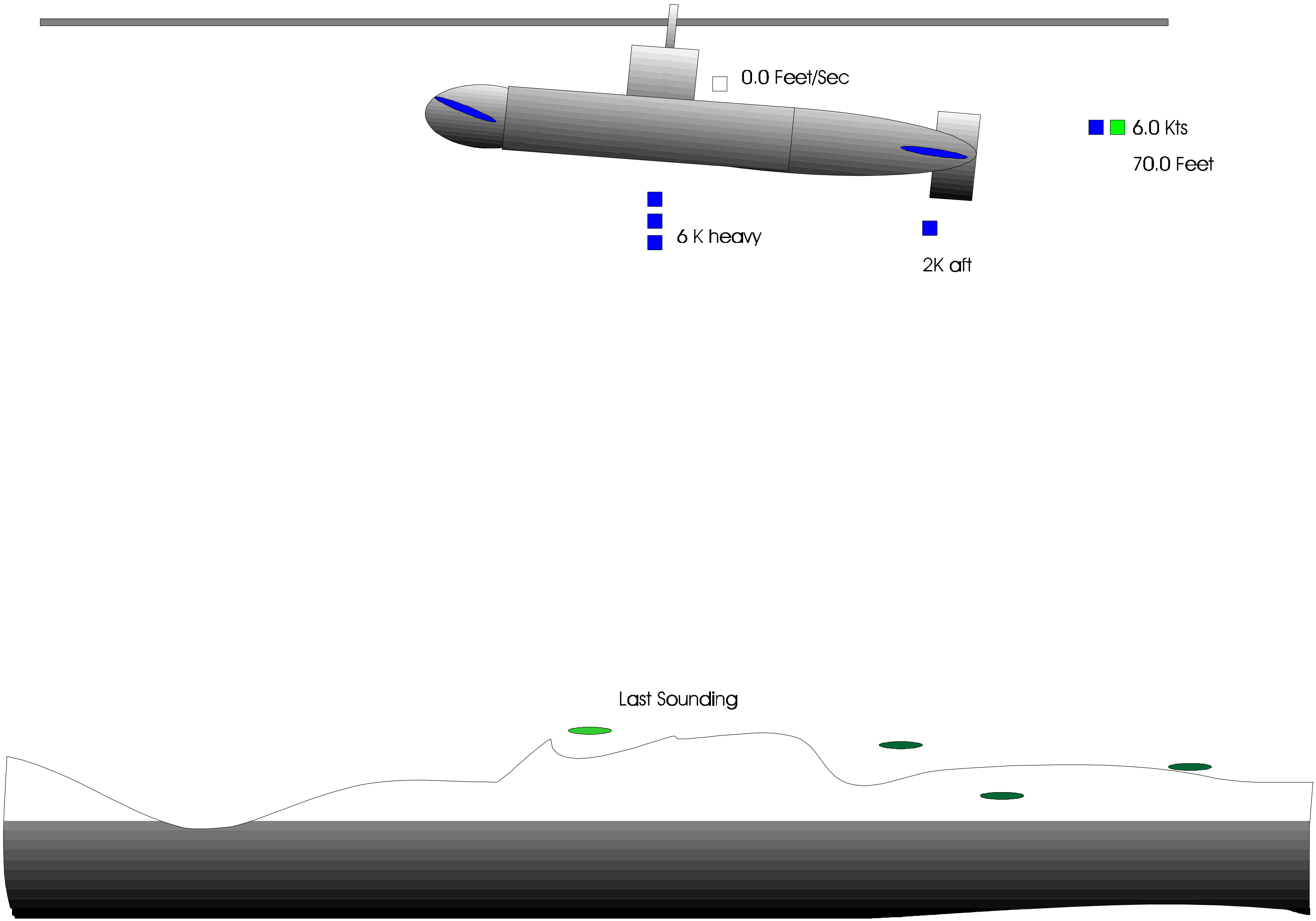
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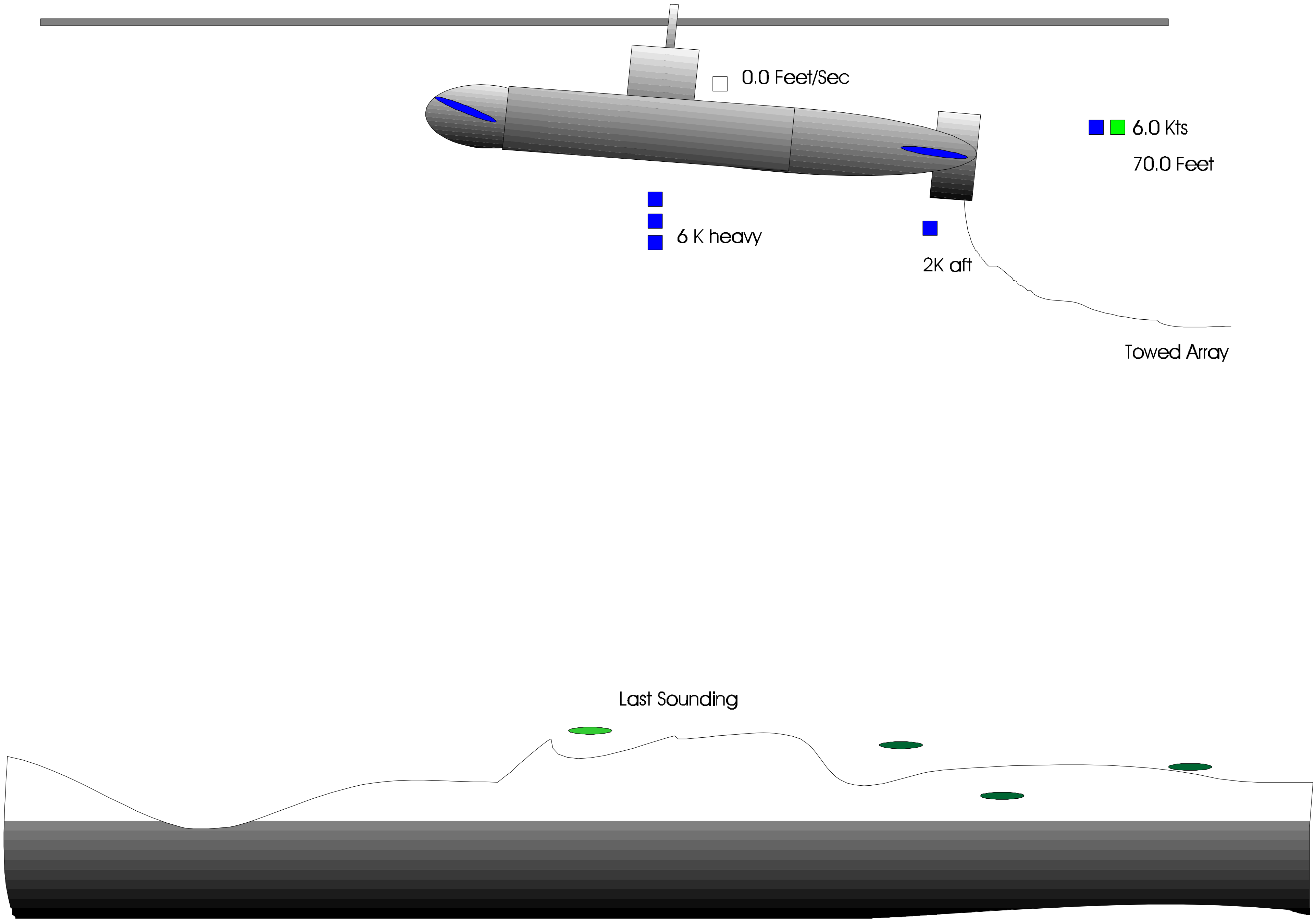
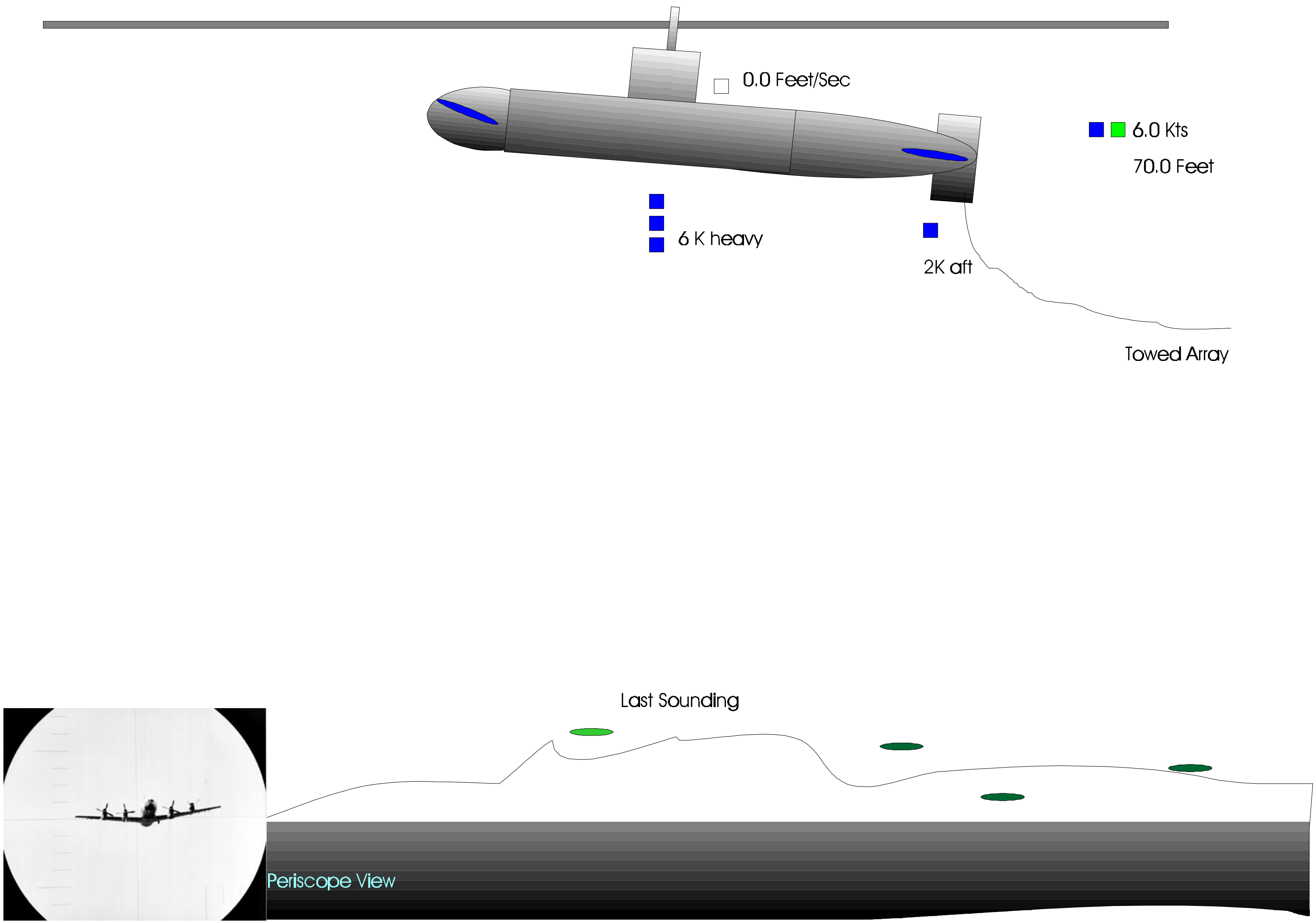
2K aft
Last Sounding


0.0 Feet/Sec
6.0 Kts
70.0 Feet
6 K heavy
2K aft
Towed Array
Last Sounding


0.0 Feet/Sec
6.0 Kts
70.0 Feet
6 K heavy
2K aft
Towed Array
Last Sounding
Periscope View

Conclusions

- Control generally improved with more states fed back
- Sliding mode control did not achieve same RMS depth error, but gave more stable control
- Overall success of feedforward suggests that disturbance display may be of value

Recommendations

- Investigate other sea states, speeds and sea directions
- Incorporate control surface rate limits
- Include control surface chatter in the optimization objective functions
- Use of Kalman filtering to provide state estimation and filtering
- Investigate the use of depth rate for feedback control in place of heave

Display Enhancement Recommendations

- Application of system identification techniques to submarine operating data to investigate the nature of the human control
- Trials of a display onboard an appropriate submarine and or a submarine dive trainer
- Use of recorded submarine operating data to provide for “instant replay” training of ship’s control personnel

Questions?

Assignment: ~~USS FLORIDA (SSBN 728) Engineer~~

USS MEMPHIS (SSN 691) Engineer

Submarine Dynamics Model

$$\dot{w} = a_{11}uw + a_{12}uq + a_{13}\sin(\quad) + b_{11}u^2 \quad {}_b + b_{12}u^2 \quad {}_s + F_d\cos(\quad) + e_{11}q^2 + e_{12}qw$$

$$\dot{q} = a_{21}uw + a_{22}uq + a_{23}\sin(\quad) + b_{21}u^2 \quad {}_b + b_{22}u^2 \quad {}_s + M_d\cos(\quad) + e_{21}q^2 + e_{22}qw$$

$$\dot{\ } = q$$

$$\dot{z} = w\cos(\quad) - u\sin(\quad)$$

$$\dot{x} = w\sin(\quad) + u\cos(\quad)$$

Implementation with Simulink